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Victoria B. Ershova[a], Andrei V. Prokopiev[b], Andrey K. Khudoley[a], Nikolay N. Sobolev[c] & Eugeny O. Petrov[c]
[a] Institute of Earth Science, Saint Petersburg State University, Saint Petersburg, Russia
[b] Diamond and Precious Metal Geology Institute, Siberian Branch, Russian Academy of Sciences, Yakutsk, Russia
[c] All Russian Geological Institute (VSEGEI), Saint Petersburg, Russia
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U/Pb dating of detrital zircons from late Palaeozoic deposits of Bel'kovsky Island (New Siberian Islands): critical testing of Arctic tectonic models

Victoria B. Ershova[a]*, Andrei V. Prokopiev[b], Andrey K. Khudoley[a], Nikolay N. Sobolev[c] and Eugeny O. Petrov[c]

[a]*Institute of Earth Science, Saint Petersburg State University, Saint Petersburg, Russia;* [b]*Diamond and Precious Metal Geology Institute, Siberian Branch, Russian Academy of Sciences, Yakutsk, Russia;* [c]*All Russian Geological Institute (VSEGEI), Saint Petersburg, Russia*

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Detrital zircon U/Pb ages provide new insights into the provenance of Upper Devonian–Permian clastic rocks of Bel'kovsky Island, within the New Siberian Islands archipelago. Based on these new data, we demonstrate that Upper Devonian–Carboniferous turbidites of Bel'kovsky Island were derived from Grenvillian, Sveconorwegian, and Timanian sources similar to those that fed Devonian–Carboniferous deposits of the Severnaya Zemlya archipelago and Wrangel Island and were probably located within Laurentia–Baltica. Detrital zircon ages from the lower Permian deposits of Bel'kovsky Island suggest a drastic change in provenance and show a strong affinity with the Uralian Orogen. Two possible models to interpret this shift in provenance are proposed. The first involves movement of these continental blocks from the continental margin of Laurentia–Baltica towards the Uralian Orogen during the late Carboniferous to Permian, while the second argues for long sediment transport across the Barents shelf.

Keywords: Arctic; New Siberian Islands; Laptev Sea; detrital zircon; late Palaeozoic; palaeogeography; provenance

Introduction

The number of detrital zircon U/Pb studies in the Arctic has increased dramatically in the past few years, providing new constraints on the palaeogeographic and tectonic evolution of the Arctic during the Phanerozoic. However, there remains a diverse spectrum of differing plate tectonic models for the evolution of the Arctic region (Lane 1997; Embry 1998; Lawver *et al.* 2002; Miller *et al.* 2006, 2010; Colpron and Nelson 2011). The eastern part of the Russian Arctic remains poorly studied, but can provide valuable control points to aid tectonic reconstructions. The New Siberian Islands have not been included in recent Arctic reconstruction due to lack of provenance data. The New Siberian Islands have been considered a Peri-Siberian tectonic block (Gramberg *et al.* 1986; Kuzmichev 2009; Danukalova *et al.* 2014) or a portion of a terrane termed 'Arctida' (Zonenshain *et al.* 1990). Metelkin *et al.* (in press) considers the New Siberian Islands to represent a small microcontinental terrane that separated from the Siberian Craton during the Neoproterozoic and Palaeozoic. Ershova *et al.* (2014) and Pease *et al.* (2014) have proposed peri-Laurentian–Baltican affinity of the New Siberian Islands. We present sediment geochemical and U/Pb detrital zircon data from Palaeozoic strata of Bel'kovsky Island. This is the westernmost island of the New Siberian Islands archipelago in the eastern part of the Laptev Sea (Figure 1) and is composed of upper Palaeozoic sedimentary rocks (Figure 2) (Kos'ko *et al.* 1985, 2013; Kos'ko and Korago 2009; Danukalova *et al.* 2014). Palaeozoic strata are deformed into wide NW-trending open folds. Mafic intrusion of Bel'kovsky Island yielded a late Permian–early Triassic age (252 ± 2 Ma) (Kuzmichev and Pease 2007). The structure of Bel'kovsky Island is complicated by small depressions filled with Palaeogene–Neogene sands and silts (Kos'ko *et al.* 1985; Proskurnin *et al.* 2012; Kuzmichev *et al.* 2013), related to Cenozoic extension across the adjacent Laptev Shelf associated with opening of the oceanic Eurasia Basin to the north (Drachev *et al.* 1999).

Stratigraphy

The Palaeozoic sedimentary succession comprises two lithologically contrasting units: relatively shallow marine platform carbonates of Middle Devonian age and basinal clastic turbidites of Upper Devonian to Permian (?) age.

The Middle Devonian Sokolov Formation

The Sokolov Formation is composed of carbonates and is the only studied formation that has an analogous chronostratigraphic equivalent on neighbouring Kotel'ny Island. According to Kos'ko *et al.* (1985), these carbonates are Eifelian–Givetian in age.

The Upper Devonian–Permian strata of Bel'kovsky Island differ significantly, both in lithology and thickness, from coeval strata on Kotel'ny Island. We have informally named them here as Formations A, B and C. Structural

*Corresponding author. Email: ershovavictoria@gmail.com

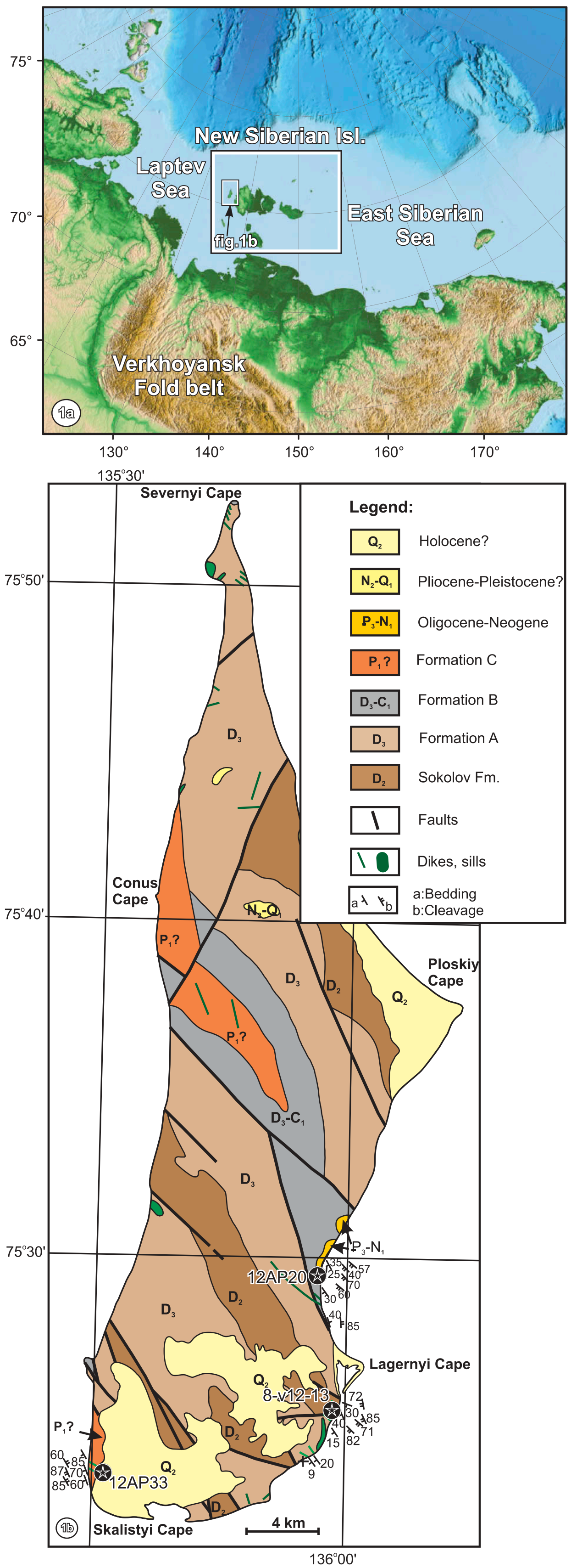


Figure 1. (a) Regional setting of the study area; (b) geological map of Bel'kovsky Island with location of study section (modified from Kos'ko *et al.* 1985).

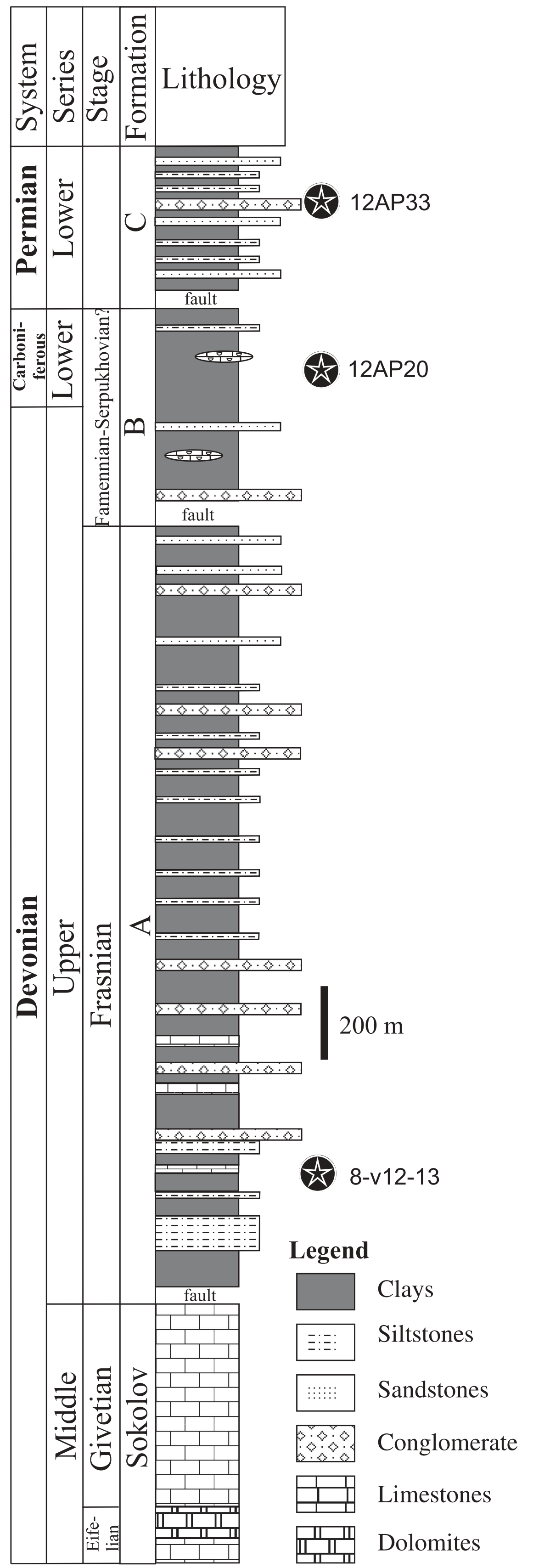


Figure 2. Composite stratigraphic sections of the of upper Palaeozoic strata of Bel'kovsky Island (modified from Kos'ko *et al.* 1985).

studies have shown that all contacts between the studied formations in the eastern and southeastern parts of Bel'kovsky Island are tectonic (Prokopiev *et al.* 2014).

Formation A (Upper Devonian, Frasnian) comprises mainly fine-grained turbidites, with numerous incised channels infilled with coarse-grained turbidites. Individual fine-grained turbidite sequences are characterized by fine-grained sandstones at the base, fining upward to siltstones and shales at the top. The coarse-grained turbidites are represented by a set of graded beds with gravelly, rarely pebbly, conglomerates. The formation age has been determined using biostratigraphical data as Frasnian (Kos'ko *et al.* 1985).

Formation B (Famennian–Tournaisian, Serpukhovian?) consists mainly of very fine-grained turbidites. They are represented mainly by siltstones and argillites, with thin beds of sandstones at the base of some graded beds. A set of channels filled in with coarse-grained turbidites have been recognized in the studied sections. Based on sparse fossils, the age of the formation has been determined as Fammenian–Tournasian (Kos'ko *et al.* 1985). The youngest zircon grain yielded a 319 Ma age (Serpukhovian), suggesting that the upper part of the formation may extend into the Serpukhovian and therefore be younger than previously considered.

Formation C (lower Permian?) has been studied in the southwestern part of the island. It is also mainly represented by fine-grained turbidites, with a predominance of argillites and siltstones whilst sandstones and conglomerates are rare. Conglomerates fill in channels of varying sizes, with pebbles mainly composed of siltstones and shales. The age of the formation was previously described as late Carboniferous (Kos'ko *et al.* 1985), however zircon dating from this study determined a cluster of youngest ages as early Permian with an age peak at 298 Ma indicating that sedimentation occurred significantly later than assumed previously.

Whole-rock chemistry

Geochemical studies were implemented at the Central Laboratory of the All Russian Geological Institute (VSEGEI), Saint Petersburg. Whole-rock major element concentrations were determined by the XRF method using an ARL 9800 spectrometer, whereas trace and rare earth elements (REEs) were determined by inductively coupled plasma mass spectrometry (ICP–MS) using an Optima 4300DV emission spectrometer and an ELAN 6100 DRC mass spectrometer. All measured concentrations are well above detection limits. Analytical uncertainties are less than 5% for major elements and generally 4–10% for trace and REE and above detection limits, except for Ni which has an uncertainty of about 15%. All geochemical data are listed in Supplementary Table 1.

REE and trace element ratios typically do not change much during diagenesis so they are used to trace sediment provenance (McLennnan 1989; McLennan *et al.* 1993, 2003; Girty and Barber 1993; references therein). We use this approach mainly to identify sedimentary reworking and to recognize input of mafic rocks from provenance source areas, which is sometimes difficult to estimate using other techniques.

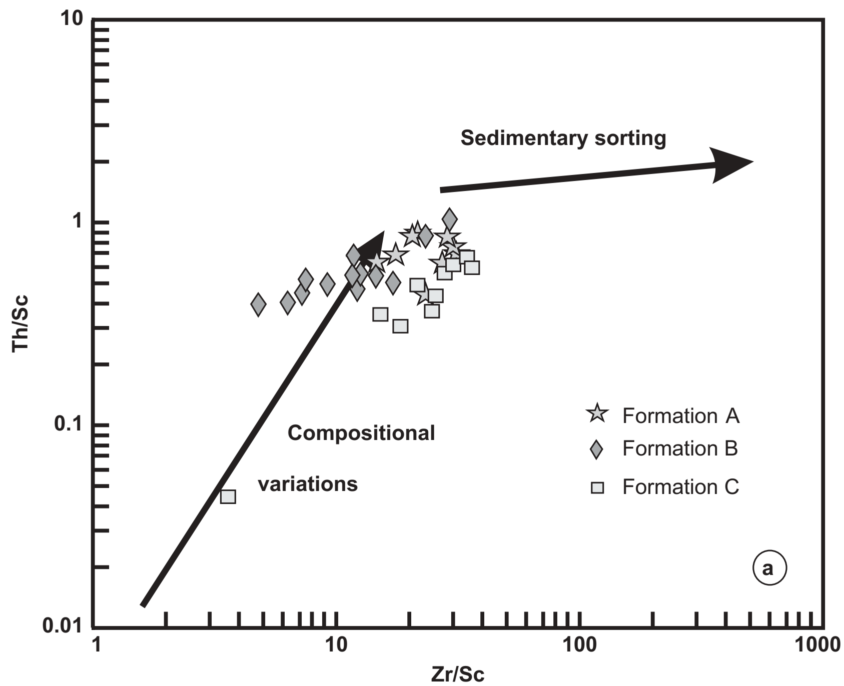
The degree of sedimentary sorting and reworking has been estimated using a Th/Sc *versus* Zr/Sc diagram (see Figure 3(a)) (McLennan *et al.* 1993). This approach is based on enrichment of zircon grains during transportation and reworking, resulting in increased Zr content in sediments.

On the Zr/Sc *versus* Th/Sc diagram, all studied samples are grouped close to the sedimentary sorting trend and point to long transportation of clastic material but without significant sedimentary reworking. The bivariate Co/Th–La/Sc diagram (Figure 3(b)) suggests predominantly felsic igneous rocks in the provenance area for all studied samples. The Upper Devonian–lower Carboniferous (Formations A and B) clastics show the spread in the Co/Th ratio that could be consistent with possible mixing of some basaltic component in the source region. The average La/Lu$_n$ values range from 5.7 to 6.3 in the Upper Devonian–lower Carboniferous strata (Formations A and B) whilst in the lower Permian deposits it reaches 9.1. These results could be interpreted as additional evidence of the existence of mafic rocks in the provenance area of the Upper Devonian–lower Carboniferous sediments.

REE distribution and the magnitude of the Eu anomaly are useful for identifying the sources of sedimentary rocks (Taylor and McLennan 1985; Condie 1993; McLennan *et al.* 1993). REE distribution in the Upper Devonian–lower Carboniferous clastics is characterized by LREE enrichment and relatively flat HREEs (Figure 4). The average values of the Eu anomaly range from 0.62 to 0.59 in Formations A and B (Upper Devonian–lower Carboniferous), respectively. These geochemical features are typical of upper continental crust (McLennan *et al.* 1993), pointing to the exposure and weathering of evolved continental crust in the provenance area. Sediments of Formation C (lower Permian) have an average Eu anomaly of 0.72. Several samples have relatively low LREE enrichment and Eu anomaly close to 1. These results point to the existence of young undifferentiated crust in the provenance area of the lower Permian sediments (McLennan *et al.* 1993).

Detrital zircon U/Pb geochronology

Geochronological studies were performed on three samples collected in the southern part of Bel'kovsky Island (Figures 1 and 2). Samples were crushed and heavy minerals concentrated using standard techniques at the Institute of Precambrian Geology, RAS. The zircon grains were



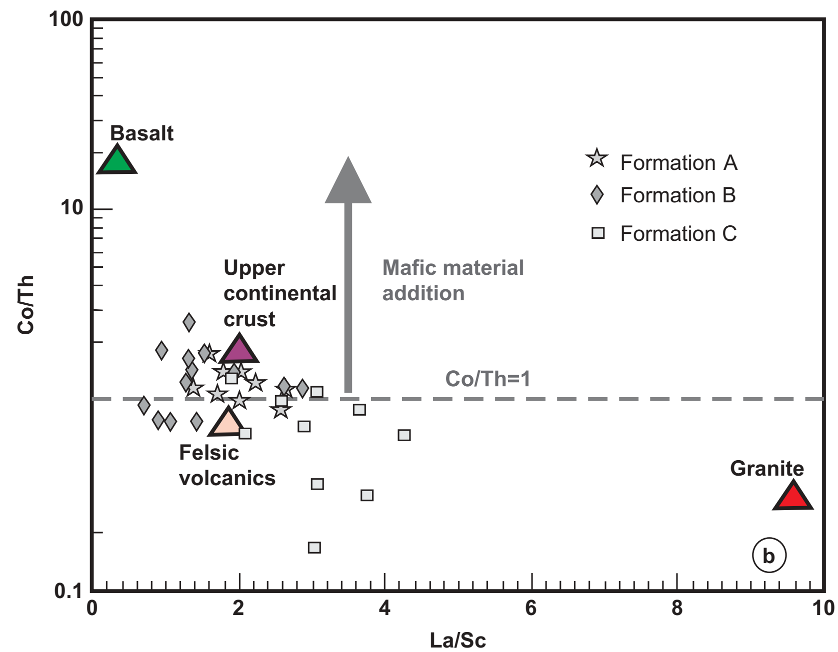


Figure 3. (a) La/Sc versus Co/Th diagrams (after Khudoley *et al.* 2001; Gu *et al.* 2002). Average compositions of volcanic rocks in plot from Condie (1993), (b) Th/Sc versus Zr/Sc diagram (after McLennan *et al.* 1993).

mounted in epoxy and polished. Further U/Pb analyses were carried out at Apatite to Zircon Inc. (Viola, ID, USA). Data tables and a description of analytical procedures are provided in the supplemental material at http://dx.doi.org/10.1080/00206814.2014.999358. At least 100 randomly picked grains were analysed in each sample. $^{207}Pb/^{206}Pb$ ages are reported for >1.0 Ga grains and $^{206}Pb/^{238}U$ ages for ≤1.0 Ga grains. Following Gehrels (2012), analyses with greater than 30% discordance and 10% reverse discordance were excluded. The results of the U/Pb study are illustrated in Figure 5.

Formation A, Frasnian (sample 8-v12-13)

This sample is dominated by Precambrian zircons (81%). Archaean age grains range from 2550 to 3725 Ma, making

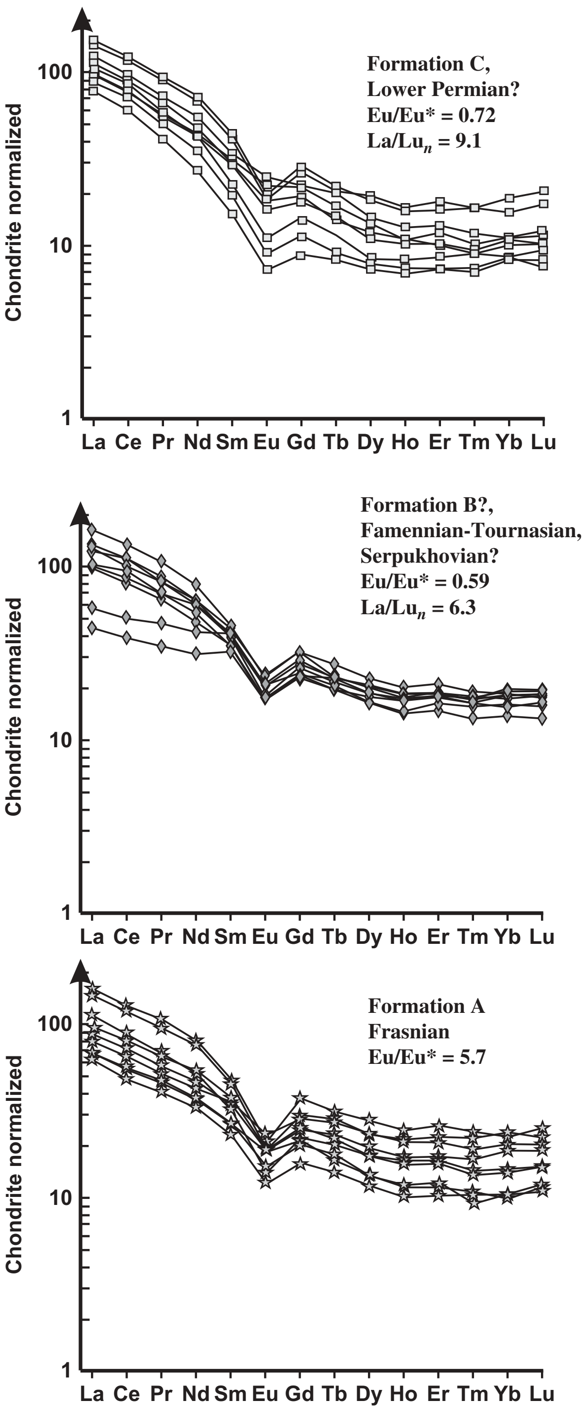


Figure 4. Rare earth element distribution of the studied samples (chondrite normalized after Taylor and McLennan 1985).

up 16% of all dated grains. Palaeoproterozoic grains contribute only 4% and form peaks at ca. 1760 and 1690 Ma. Mesoproterozoic grains (42%) form several distinct peaks at 1509, 1324 and 1111 Ma. Neoproterozoic grains (19%) are grouped in several populations with peaks at 987, 636 and 578 Ma. Palaeozoic zircons (22%) form peaks at ca. 537, 480 and 425 Ma. There are only a few Devonian age grains that are close to the age of sedimentation.

Formation B, Famennian–Tournaisian, Serpukhovian? (sample 12-AP-20)

Eighty-three per cent of the dated zircons in Formation B are of Precambrian age. Archaean grains comprise 4% of the population, whilst Palaeoproterozoic zircons (10%) form peaks at 1647 and 1762 Ma. Mesoproterozoic grains (35%) define several populations at ca. 1511, 1280 and 1180 Ma. Neoproterozoic grains comprise 34% of the population and are grouped in peaks at 955 and 639 Ma. Palaeozoic zircons (19%) have major peaks at 550, 470 and 426 Ma.

Formation C, lower Permian? (sample 12-AP-33)

Precambrian grains contribute 30% of the zircon population. Archaean and Palaeoproterozoic grains contribute 10% and 5%, respectively, and do not form significant peaks. Mesoproterozoic (5%) and Neoproterozoic (10%) zircons are grouped into small peaks at ca. 790 Ma. The sample is dominated by Palaeozoic zircons (70%) forming distinct peaks at 476, 390, 330, and 298 Ma.

Provenance interpretation and revision of Arctic Palaeozoic tectonic models

The detrital zircon populations from Upper Devonian–lower Carboniferous strata (Formations A and B, Figure 5) are very similar. The oldest zircon ages are Archaean, forming a small peak at 2785 Ma (Figure 5). These Archaean ages could be derived from any of a number of Archaean continental blocks across the Arctic.

The 2.0–1.3 Ga detrital zircon population is attributable to the early evolution of the Grenville Province (McLelland *et al*. 2010), as well as to the ages of numerous Mesoproterozoic to latest Palaeoproterozoic terranes within the Sveconorwegian orogen (Bingen *et al.* 2008). The presence of 1090–940 Ma detrital zircon populations in Upper Devonian–lower Carboniferous strata suggests a significant sediment contribution from the Grenvillian–Sveconorwegian orogeny (Bingen *et al.* 2008; Rivers 2008). Grenvillian–Sveconorwegian detrital zircons have been widely reported from numerous localities in the Arctic, including Novaya Zemlya (Lorenz *et al.* 2013), Severnaya Zemlya (Lorenz *et al.* 2008), Wrangel Island (Miller *et al.* 2010), Seward Peninsula (Amato *et al.* 2009), and the Canadian Arctic Islands (Anfinson *et al.* 2012a, 2012b).

The Neoproterozoic to earliest Palaeozoic grains (500–700 Ma) are attributed to the Timanian Orogeny. The Timan Fold Belt formed as the result of terrane accretion onto the northeastern margin of Baltica (Gee

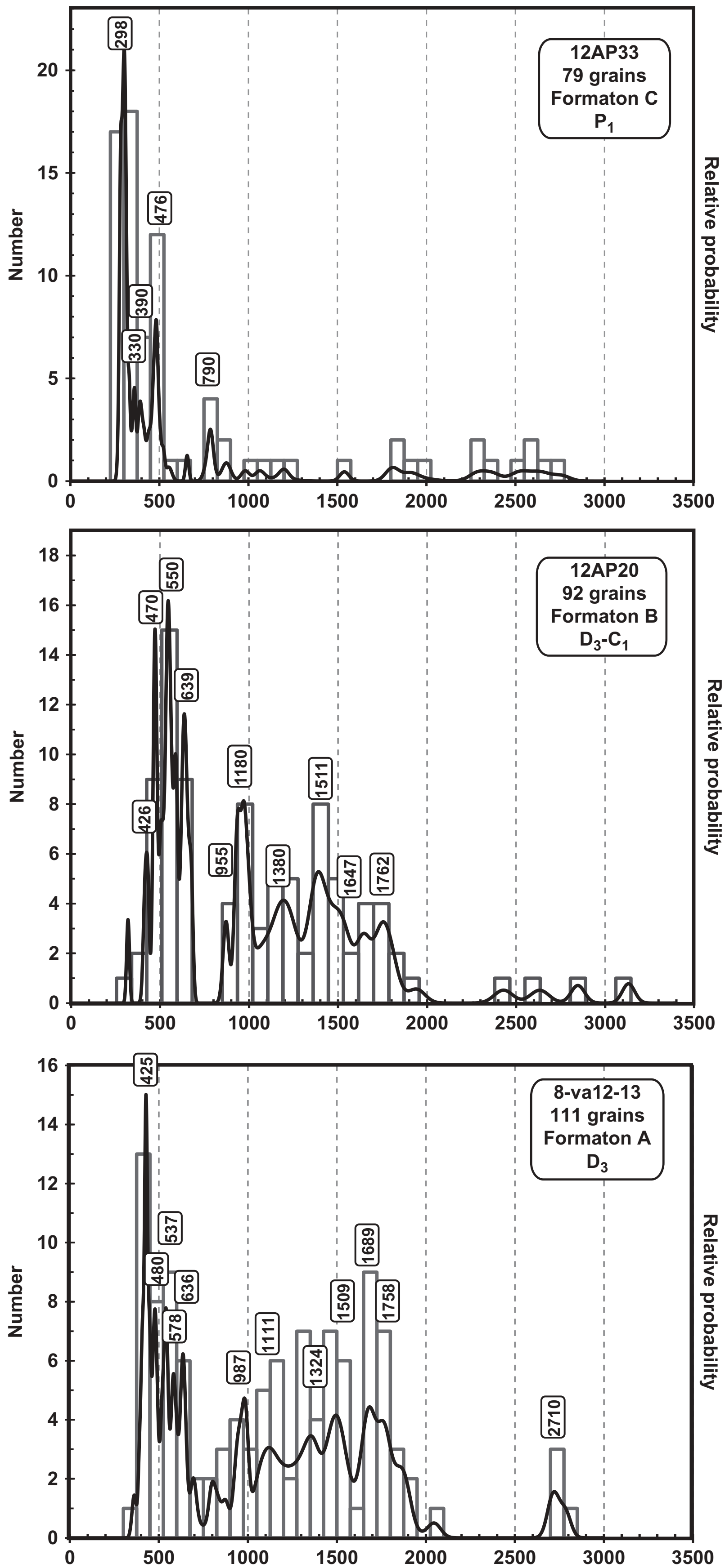


Figure 5. Probability distribution plots of U/Pb ages of studied samples (upper Palaeozoic clastics, Bel’kovsky Island).

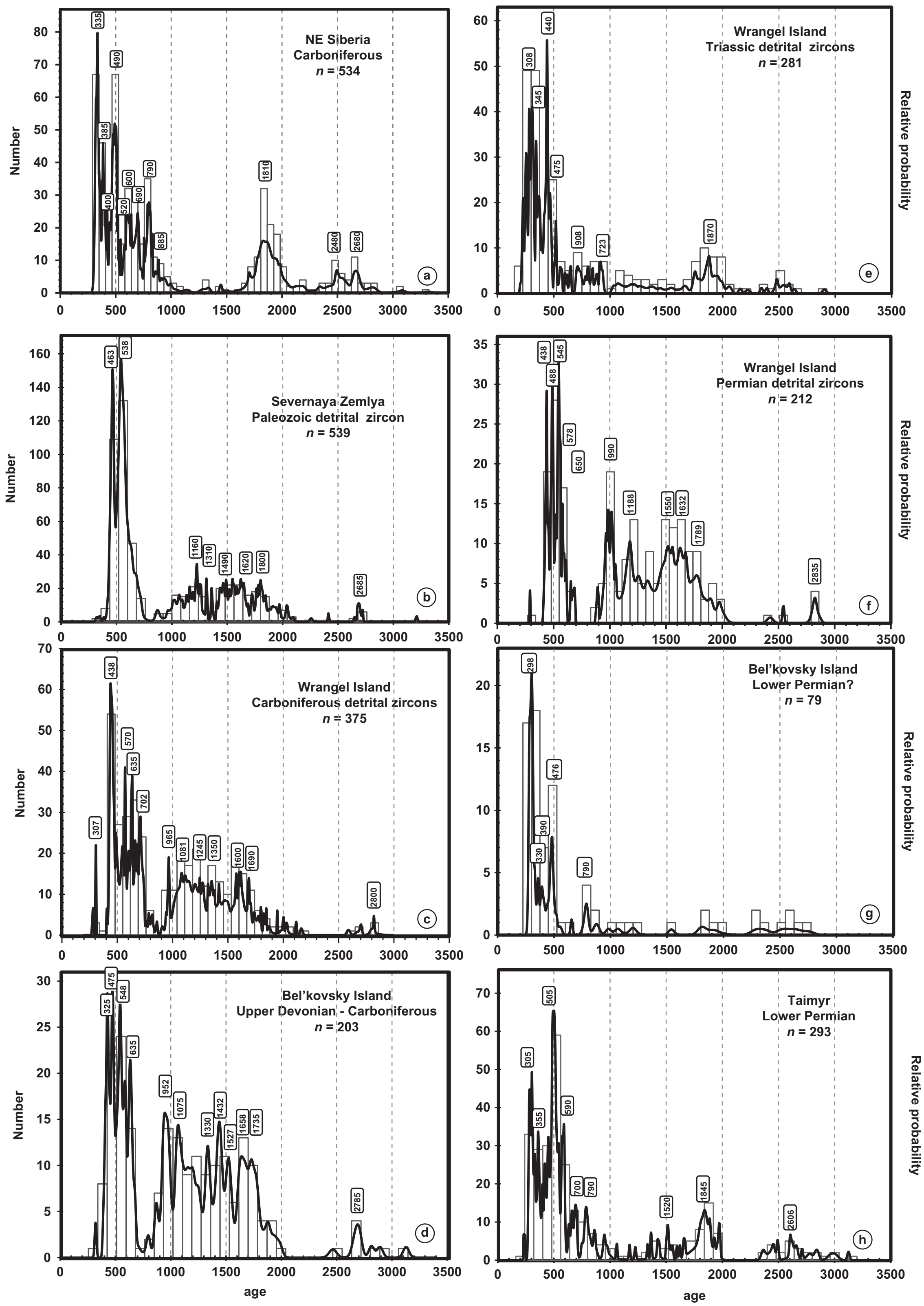


Figure 6. Comparison of U/Pb age distributions of detrital zircon populations: (a) Carboniferous detrital zircons of northeast Siberia (Ershova *et al.* 2013; Prokopiev *et al.* 2013); (b) Palaeozoic detrital zircons of Severnaya Zemlya (Lorenz *et al.* 2008); (c) Carboniferous detrital zircons of Wrangel Island (Miller *et al.* 2010); (d) Formations A and B (Upper Devonian–Carboniferous) (this study); (e) Triassic detrital zircons of Wrangel Island (Miller *et al.* 2010); (f) Permian detrital zircons of Wrangel Island (Miller *et al.* 2010); (g) Formation C (lower Permian?) (this study); (h) Permian detrital zircons of Taimyr (Zhang *et al.* 2013).

and Pease 2004), and expressed by several episodes of granitoid magmatism (Gee *et al.* 2000; Kuznetsov *et al.* 2007; Orlov *et al.* 2011). Zircons of Timanian age have been reported from many Arctic localities (Lorenz *et al.* 2008, 2013; Amato *et al.* 2009; Pease and Scott 2009; Beranek *et al.* 2010; Miller *et al.* 2010; Pease 2011; Anfinson *et al.* 2012a, 2012b). The 380–470 Ma populations are likely to be related to the Caledonides. The prominent peak at ca. 470 Ma represents an early stage of the Caledonian orogeny, whilst the late Silurian–Early Devonian ages correspond to the main Scandian phase of deformation (McKerrow *et al.* 2000).

Thus our data suggest that the Upper Devonian–lower Carboniferous clastic strata of Bel'kovsky Island suggest a provenance from the Sveconorwegian, Grenvillian, Timanian, and Caledonian orogenies and/or from the terrane with their provenance fingerprints. Whole-rock chemistry data also point to the exposure of evolved crust in the provenance area. The New Siberian Islands have been considered by some authors as a distal part of the Siberian shelf (Gramberg *et al.* 1986; Kuzmichev 2009; Danukalova *et al*. 2014); however Siberia was not involved in the Grenvillian, Timanian, or Caledonian orogenies (Parfenov 2001). The distribution of detrital zircons from the Carboniferous strata of northeastern Siberia (Ershova *et al.* 2013; Prokopiev *et al.* 2013) (Figure 6) is very different from the results obtained from Bel'kovsky Island in this study. Therefore we conclude that Siberia should not be considered as a provenance area for the Upper Devonian–lower Carboniferous clastic rocks of Bel'kovsky Island.

The detrital zircon ages obtained from the studied samples are however very similar to those from Devonian–Carboniferous deposits of Severnaya Zemlya and Wrangel Island (Figures 6 and 7). The cumulative probability plots (Figure 7) point to the same provenance area for the Devonian–Carboniferous successions of New Siberian Islands (Bel'kovsky and Kotel'ny Islands), the Severnaya Zemlya Archipelago and Wrangel Island. The presence of Grenvillian, Timanian and Caledonian ages permits a reconstruction of these terranes to sit adjacent to the northern margin of Laurentia–Baltica (Figure 8).

The distribution of detrital zircon ages within the lower Permian (?) deposit is very different from that in older strata (Figure 5). The Precambrian grains contribute 30% of the zircon population and do not have Grenvillian or Timanian fingerprints. Small peaks at ca. 2600 and 790 Ma do not give a definitive tie to a particular source region. The primary population has a peak at 298 Ma and can be attributed to the main collision phase in the Arctic of the Uralian orogen. The secondary peak at ca. 330 Ma can be correlated to a widespread subduction-related magmatic episode in the Urals (Brown *et al.* 2008). The 400–480 Ma population is interpreted to have come from an early Palaeozoic arc accreted to Baltica during the Uralian orogenesis. The geochemical data also point to the presence of young undifferentiated crust in the provenance area. The results of U/Pb studies of Permian deposits from the New Siberian Islands (this study, Ershova *et al.* 2014; Pease *et al.* 2014) therefore suggest a drastic change in sediment source area from mainly Laurentian–Baltican evolved crust during the Late Devonian–early Carboniferous, to the Uralian orogeny

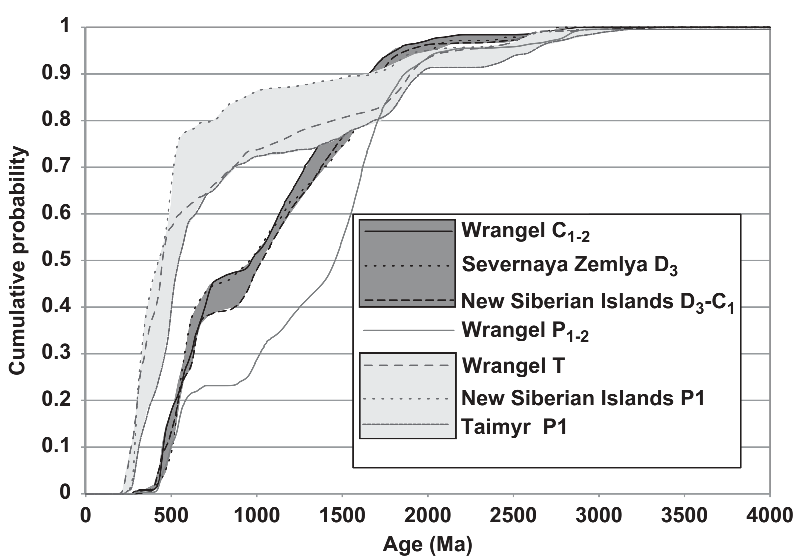


Figure 7. Cumulative probability diagram for Upper Devonian–Permian samples of the New Siberian Islands (this study, Ershova *et al.* 2014; Pease *et al.* 2014), Upper Devonian samples of Severnaya Zemlya (Lorenz *et al.* 2008) and Carboniferous, Permian, and Triassic samples of Wrangel Island (Miller *et al.* 2010).

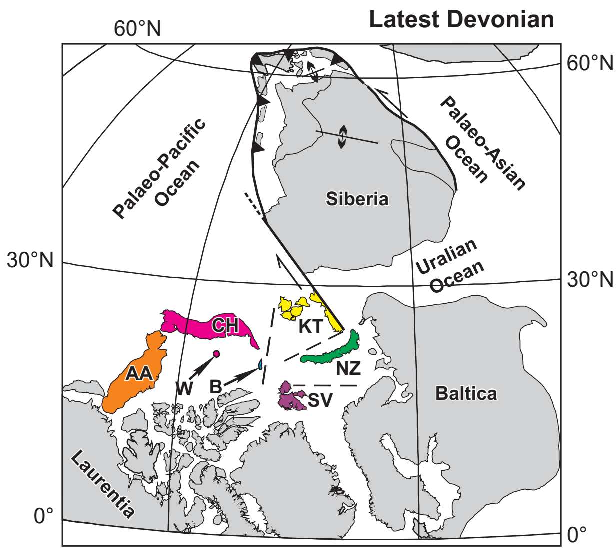


Figure 8. Palaeogeographic model for the late Devonian (modified Lawver *et al.* 2002; Miller *et al.* 2010). AA, Arctic Alaska; CH, Chukotka; W, Wrangel Island; SV, Svalbard; KT, Kara terrane; NZ, Novaya Zemlya; B, Bel'kovsky Island.

by the Permian. The detrital zircon ages obtained from the Permian sandstones of the New Siberian Islands are also very similar to those from the lower Permian deposits of Taimyr (Zhang *et al.* 2013) and Triassic deposits of Wrangel Island (Figures 6 and 7).

A major outstanding question remains, concerning the transport paths of zircons carrying Uralian fingerprints. So far we have proposed two possible models that need to be tested by further work (Figure 9(a) and 9(b)). The eastward movement of Chukotka and Wrangel Island has been proposed by (Miller *et al.* 2010, 2013). Devonian–Carboniferous rifting, which was widespread across the Arctic (Nikishin *et al.* 1996; Dewey and Strachan 2003; Miller *et al.* 2011), could trigger the eastward movement of Bel'kovsky Island (with Severnaya Zemlya and Wrangel), and therefore the initiation of the opening of the Amerasia basin may have occurred earlier than previously assumed (Figure 9(a)). Another possible trigger of this movement could be that proposed by Colpron and Nelson (2011) as the Northwest Passage hypothesis, with eastward movements of different Arctic terranes in the Palaeozoic.

An alternative model explaining the drastic shift in the provenance area involves the long transportation of clastics across the Barents shelf (Figure 9b). Conversely, this model does not require the rifting of continental blocks comprising Bel'kovsky Island, Severnaya Zemlya, and Wrangel Island from Laurentia–Baltica prior to the Mesozoic. Further work is required in both the western and eastern Arctic to identify sediment transport pathways from the Uralian Orogen across the region and to complete the latest Palaeozoic tectonic history. Pease *et al.* (2014) explain the drastic shift in the sediment provenance involving collision of Baltica–Kara (including the New Siberian Islands?) with northern Siberia. The Carboniferous–Permian granites have been reported from the Severnaya Zemlya Archipelago and Northern Taimyr and interpreted as evidence of collision across the region (Vernikovsky 1996; Makariev 2012; Pease *et al.* 2014; and references therein), whilst there are not any late Palaeozoic granites within the New Siberian Islands Archipelago (Kos'ko *et al.* 1985). The Laurentian–Baltican provenance of pre-Permian deposits point to non-Siberian affinity of the Archipelago; so far the late Mesozoic granites and ophiolites described from the New Siberian Islands are the only evidence of collision and they are Early Cretaceous in age (Kos'ko and Korago 2009).

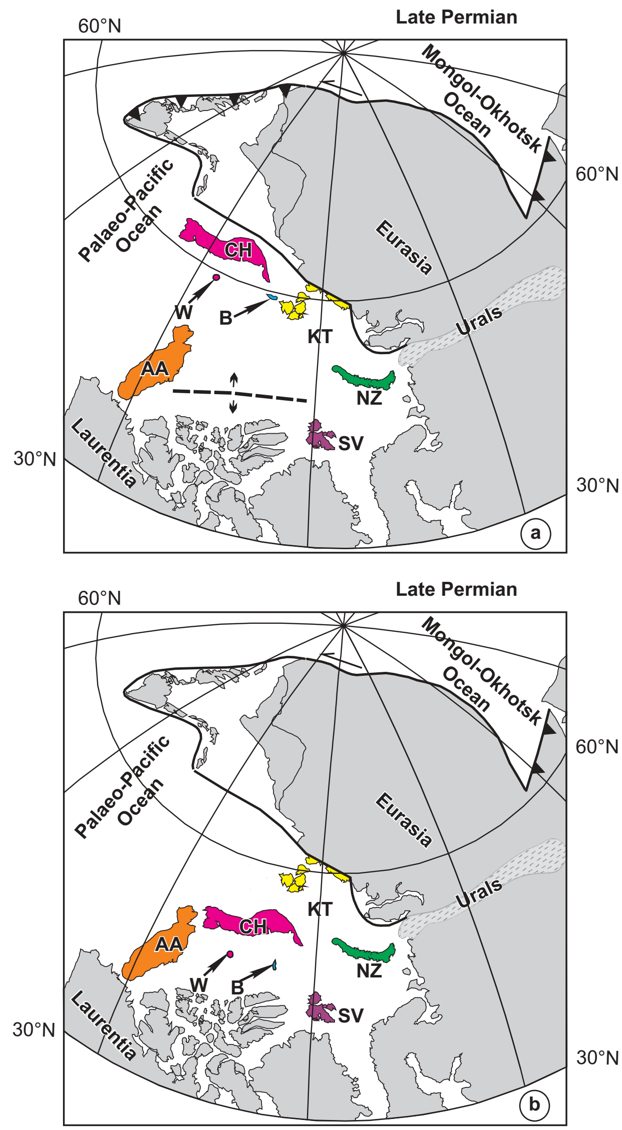


Figure 9. Two possible palaeogeographic models for the Permian (modified Lawver *et al.* 2002; Miller *et al.* 2010) (for description of abbreviations see Figure 8).

Conclusions

Detrital zircon data from the Upper Devonian–lower Carboniferous strata of Bel'kovsky Island and the wider New Siberian Islands were derived from a provenance area associated with the Grenvillian–Sveconorwegian, Timanian, and Caledonian orogenies. The distribution of detrital zircons reveals almost identical provenance for Devonian–Carboniferous sediments on the New Siberian Islands, the Severnaya Zemlya archipelago, and Wrangel Island, suggesting that these continental blocks were close to each another during the Devonian–early Carboniferous, with a connection to Laurentia–Baltica. The contrasting detrital zircon population from the lower Permian clastics has a clear signature of the Uralian orogen.

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Supplemental data

Supplemental data for this article can be accessed at http://dx.doi.org/10.1080/00206814.2014.999358.

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